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CLASSIFICATION UNCLASSIFIED	SYSTEM NUMBER 507242 
TITLE AN OVERVIEW OF SOME CURRENT RESEARCH ON WELDING RESIDUAL STRESSES AND DISTORTION IN THE U.S. NAVY	
System Number: Patron Number: Requester:	
Notes: Paper #39 contained in Parent Sysnum #507203	
DSIS Use only: Deliver to: DK	

Report Documentation Page		Form Approved OMB No. 0704-0188
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1. REPORT DATE 01 OCT 1997	2. REPORT TYPE	3. DATES COVERED 00-00-1997 to 00-00-1997
4. TITLE AND SUBTITLE An Overview of Some Current Research on Welding Residual Stresses and Distortion in the U.S. Navy		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER	
	5e. TASK NUMBER	
	5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Surface Warfare Center, 9500 MacArthur Blvd , West Bethesda, MD, 20817-5700		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

a. REPORT
unclassified

b. ABSTRACT
unclassified

c. THIS PAGE
unclassified

17. LIMITATION OF
ABSTRACT

**Same as
Report (SAR)**

18. NUMBER
OF PAGES

25

19a. NAME OF
RESPONSIBLE PERSON

An Overview of Some Current Research on Welding Residual Stresses and Distortion in the U.S. Navy

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ABSTRACT

This paper describes some of the current U.S. Navy efforts geared toward managing residual stresses and distortion during weld fabrication. These efforts include model development, model verification, thermo-mechanical and thermo-physical property development, the generation of residual stress measurement data using x-ray and neutron diffraction techniques, the analysis of the effects of residual stresses on fatigue and stress corrosion cracking, and the use of weld residual stresses to achieve desired shapes in part manufacturing.

Due to the complexities involved in weld residual stress development, significant emphasis has been placed on modeling. The importance of experimental data for model development and validation has been emphasized. It was shown that there were some differences between FE models and experimental results, but in general both were in good agreement. However, it was also shown that residual stress development is highly dependent upon the details of the fabrication process and the material properties and characteristics. Little difference between thermo-mechanically coupled and uncoupled FE results were demonstrated, but additional work is necessary since the work presented here did not include phase transformation effects or varying material properties representative of remelted or reheated material.

Careful experimental techniques for measuring residual stresses must be employed to obtain reliable neutron diffraction and x-ray diffraction results for comparing to model analysis. It was shown that welding creates a wide variation in material properties, and can therefore significantly affect measurement results. This was attributed to dilution and thermal cycling that occurs during welding. It was also shown that when analyzing x-ray diffraction results, it is important to realize that the technique is a surface analysis method and can therefore be influenced by surface conditions. Grinding stresses played an overwhelming role in masking the surface residual stresses developed by welding. However, the grinding stresses were able to be subtracted from the overall stress state to determine the surface stresses due to welding only. A comparison of surface residual stresses and bulk, through thickness stresses indicated that the surface stress state is not representative of the internal stress state.

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but intermittent welding and thermal tensioning could provide the desired reduction in distortion. The data generated by this empirical model also suggested that the initial plate flatness could also provide some benefit regarding distortion mitigation.

In a study on the effects of residual stresses on fatigue, it was shown that residual stresses play an important role in determining fatigue properties of materials. It was also shown that there was no difference in the fatigue crack growth rate of specimens containing residual stresses and those that did not. This was because the crack tip stress field appeared to obliterate the existing residual stresses out to about 1mm ahead of the tip so that the growing crack is never subjected to these stresses. In another study, weldments were subjected to SCC conditions. This study showed no crack initiation and limited crack growth as a result of weld residual stresses. However, this study was inconclusive due to crack location discrepancies and the possible existence of compressive residual stresses in the crack tip areas.

Introduction

Weld Residual Stress Formation

The formation of weld residual stresses is quite complex. Residual stress development and distribution are dependent on nearly every variable associated with weld fabrication as well as the mechanical and thermo-physical properties of the materials involved. This is because these variables directly affect the two basic factors which determine residual stress development: differential contraction and volumetric phase changes. Some of the variables are listed below:

- *Material Thickness*
- *Joint Geometry*
- *Welding Process and Parameters*
- *Heat Input*
- *Restraint*
- *Bead Sequencing*
- *Preheat and Interpass Temperature*
- *Welding Position*

Although the qualitative effects of welding variables affecting residual stresses are understood independently, it is the complex interactions which pose the greatest difficulty in predicting the quantitative outcome for a given set of conditions. However, some advances have been made in this direction and are the topic of this paper.

Cracking Concerns

For the most part, the existence of tensile residual stresses in welded structures is considered undesirable. The presence of residual stresses can lead to cracking which can ultimately result in structural failure. Some types of cracking which can occur due to the presence of residual stresses are listed below:

- *Solidification and Hot Cracking*
- *Hydrogen Cracking*
- *Stress Corrosion Cracking*
- *Fatigue Cracking*
- *Corrosion Fatigue Cracking*

Weld residual stresses can contribute to the initiation, propagation or acceleration of these cracking types. The ability to know or control any one of the conditions that contribute to the onset of cracking is a distinct advantage in controlling the outcome. Unfortunately, the precise level and distribution of residual stresses are seldom known.

Design Concerns

It is common practice in design, or fitness-for-service assessments to assume yield level residual stresses in the absence of actual measurements. It is also difficult to determine the distribution of stresses under any one set of conditions. This can lead to excessively conservative results. For example, a structural member may require a greater

thickness due to the assumption of yield level residual stresses, when, in fact, less than yield level residual stresses are present. Therefore, the thicker design requirement results in a heavier structure. In some cases additional weight may come with no other sacrifice, but in the case of shipbuilding, additional weight means slower speeds, increased fuel consumption, and a decreased capacity for additional future equipment. It is therefore desirable to optimize design and fitness-for-service analyses by utilizing appropriate inputs relative to residual stresses and their distributions.

Distortion Concerns

The trend in both military and commercial shipbuilding is to increase the use of higher strength steels. This means that thinner sections can be utilized to achieve the same structural load carrying capacities while reducing structural weight, thereby increasing payload capacity, reducing fuel costs, and increasing speed.

The cost of lighter weight structures comes at a large cost in terms of distortion control. It has been estimated that distortion costs \$3.4 million per ship. [1] This cost includes labor costs for flame straightening, and other down-stream effects associated with replacement of materials, interruption of other trades, and increased fitting time. Once the ship is underway, distortion can also reduce hydrodynamic performance, causing decreased speed and increased fuel consumption. Distortion is also detrimental to the buckling resistance, thus reducing the capabilities and load carrying capacity of a ship.

Prevention, Control and Correction of Weld Residual Stresses and Its Adverse Side Effects

There are several methods that have been used to deal with the adverse effects of weld residual stresses. The methods have been quite diverse but they can be defined by three basic categories. They are 1) preventive, 2) control, and 3) corrective measures. The term "preventive," as used here, means to minimize the development of weld residual stresses in order to reduce or eliminate adverse side effects (e.g. minimize fillet weld size to reduce the amount of shrinkage to the point of reduced distortion). The term "control," means to manage the effects of residual stresses to the point of a desirable outcome (e.g.. presetting a butt welded plate to achieve a flat plate at the completion of welding). "Corrective" means to reverse the outcome in order to minimize or reduce the adverse side effect (e.g. flame straightening of thin section panels subsequent to welding to reduce distortion within fairness requirements). Some methods for dealing with the adverse side effects of residual stresses, which have been used in the past, or are being considered for use by the U.S. Navy are listed below in Table 1.

Table 1. Some methods for preventing, controlling, and correcting weld residual stresses and their adverse effects.

Preventive	Control	Corrective
Minimize Weld Size/Heat Input	Pre-bending or Presetting	Flame Straightening
Thermal Tensioning	Back-stepping/Wandering	Post-heating
High Speed Welding	Bead Sequencing	
Intermittent Welds	Increased Restraint	
Flatter Plate	Chilling	
Mechanical Tensioning		
Preheating		
Dimensional Accuracy Control		

The ideal solutions are methods that are preventive. These methods reduce the development of residual stresses and hence the propensity for adverse side effects. Other methods counteract the anticipated side effect but do not necessarily reduce or eliminate the propensity for residual stress development. Therefore, their effects can be temporary. For example, it has been the experience of the U.S. Navy that some thin section bulkheads require repeated flame straightening at various stages of assembly in order to meet unfairness requirements. This is probably due to the fact that the residual stresses are not being removed by flame straightening, but rather redistributed. This redistribution results in free plate edges which are wavy in nature. These wavy edges must then be forced into position for welding to the adjacent plate. At the completion of ship assembly and after several flame straightening events, the final structure must also be flame straightened to meet unfairness requirements. This process of fixturing, welding and flame straightening is a

viscious cycle that only aggravates the overall residual stress situation. The ability to minimize residual stresses and distortion from the initial stages of fabrication would diminish the cumulative effects throughout the complete assembly.

Some Positive Aspects of Weld Residual Stresses

In most cases, the existence of residual stresses is considered to be detrimental. However, not all residual stresses have negative effects. The presence of compressive stresses can provide positive effects in terms of material performance. Since tensile stresses are necessary to initiate and propagate cracks, the existence of compressive stresses can eliminate this problem. But in order to produce compressive stresses, a balance of tensile stresses will also exist elsewhere. In order to use residual stresses as an advantage, it is necessary to distribute them properly. In the case where peening is used to avoid fatigue crack initiation, compressive stresses are imparted on the surface of the material through plastic deformation. The balance of tensile stresses exist below the surface where they will not have an effect on fatigue crack initiation, since fatigue cracks generally initiate at the surface. In terms of welding, controlling the distribution of residual stresses to achieve the desired distribution of stresses is extremely complex due to the many variables associated with the process.

Needs

There is a need to generate specific information relative to the benefits of techniques proposed to prevent, control, or correct residual stresses. Although the shipbuilding industry has taken some measures to control residual stresses, satisfaction has not been fully achieved. Some shipbuilders have gone as far as redesigning and rebuilding fabrication lines. For the most part, the countermeasures against residual stresses and distortion have been activated within the framework of existing fabrication lines. However, shipbuilders have been justifiably reluctant to invest significant capital in new equipment without sufficient evidence that some benefit will be achieved.

The development and demonstration of methods for preventing, controlling or correcting residual stresses, requires the aid of computer models and experimental data due to the vast complexity of the problem. In addition to empirical data, modeling provides the ability to perform experimentation on a computer without actually performing the experiments. However, it is essential that models be validated over a large range of conditions with sufficient, well-controlled experiments. The use of modeling could lead to means of controlling residual stress formation by either eliminating them, or by managing them to achieve some benefits.

Objectives

- Develop further understanding of residual stress formation and their interactions with their effects.
- Develop a quantitative understanding of how to reduce the residual stresses and their effects.

Approach

The approach to reducing or controlling residual stresses and their effects, as a result of welding, involves gaining a full understanding of the synergistic effects of the variables. The qualitative effects of individual variables are somewhat understood. The quantitative, synergistic effects are not well defined. Considering all of the variables that can affect residual stress development, it would be a monumental task to sort the quantitative effects through experimentation. Therefore, emphasis has been placed on model development to aid in understanding the complex interaction of variables.

For modeling to be a reliable means of predicting residual stresses, it is essential to develop the pertinent thermo-mechanical and thermo-physical properties. As part of the Navy program, a database is being developed which is a compilation of thermo-mechanical and thermo-physical properties. Data is being gathered from various sources for inclusion in the databases. Thermo-mechanical data is also being developed, specifically high temperature strength properties.

It is also necessary to validate the models with experimentation to the extent that reasonable agreement with experiments has been achieved over a large range of conditions. Therefore, controlled experimentation has been conducted which represents somewhat simplistic conditions, such as a stationary GTA spot weld, to more complex conditions such as a moving GMA multipass weld.

An essential part of managing residual stresses also involves developing an understanding of the effects that these stresses have on material performance. Efforts are also being pursued to determine the effects of residual stresses on fatigue performance and stress corrosion cracking. In both cases, residual stresses were induced in test samples to evaluate material performance.

Currently, the problem demanding the most attention relative to weld residual stresses is distortion in welded thin section panels as a result of bulkhead fabrication. In order to provide solutions in a short time frame, a practical approach, based on engineering analyses, was taken rather than an approach based totally on a first principles model. A predictive methodology was developed, thermo-mechanical properties were developed in support of the predictive methodology, and proposed solutions were evaluated using the predictive methodology.

Description of Work and Results

Modeling and Validation of Residual Stress Distributions in and HSLA-100 Disk

The purpose of this work was to validate residual stress models currently under development at Oak Ridge National Laboratory (ORNL). The details of this work are presented in References [2] and [3]. The residual stress distribution in a GTA spot welded, 19 mm thick, HSLA-100 steel disk (welded at the Naval Surface Warfare Center) was simulated using thermo-mechanically uncoupled and semi-coupled finite element (FE) formulations at ORNL and measured using neutron diffraction techniques at the National Institute of Standards and Technology (NIST). The process details are given in Figure 1.

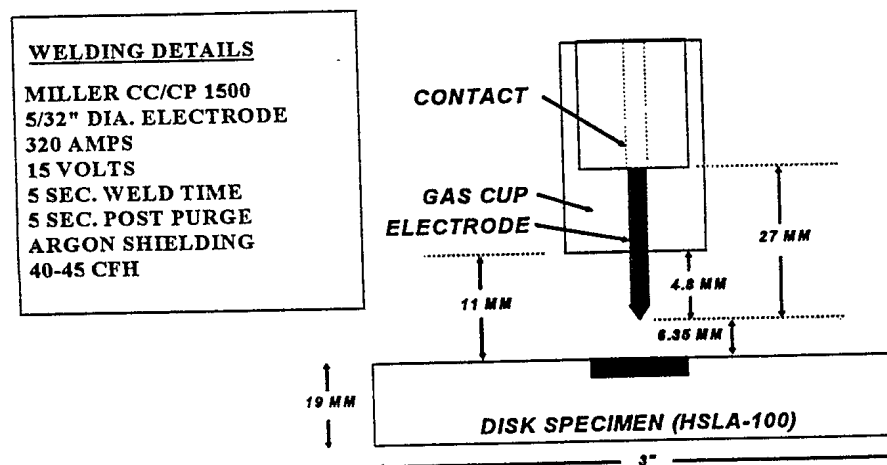


Figure 1. Process details of GTAW stationary spot weld.

The uses of the GTAW process, the absence of filler metal, the stationary plasma, and the symmetrical heat flow represent a very simplistic condition for residual stress development and modeling. The formation of welding residual stresses in HSLA-100 steel is a thermo-mechanical - metallurgically coupled phenomenon. In order to model such a situation, it requires a thorough knowledge of the thermal, mechanical, and phase transformation phenomena and their interaction. In alloys such as austenitic stainless steels, which do not experience solid state phase transformations during welding, the metallurgical effects can be readily ignored or uncoupled from the thermo-mechanical aspects. As to the thermo-mechanical coupling, it is a common opinion that the coupling could be regarded as only a one-way process, that is, the mechanical responses of a weldment do not strongly influence its thermal behaviors during the course of welding. In this case, both a semi-coupled and uncoupled approaches were applied to the same weldment to compare to each other and to the actual neutron diffraction measurements. The purpose of the dual model approach was to determine whether the different FE formulations would result in any differences in predicting the residual stresses during welding. The microstructural changes in the HAZ and fusion zone were not included at this stage, in an attempt to provide the baseline information for on-going model development that will eventually include all the thermo-mechanical-metallurgical coupling effects.

In general, there was little difference between the results of the uncoupled and the semi-coupled models (Figure 2). There was also good agreement between either model and the neutron diffraction measurements in the far HAZ and the base metal. However, in the near HAZ and the fusion zone, predictions from both models are higher than those measured. The cause for these discrepancies can be complicated. Only the properties for the base metal were used in the model calculations. Any hardening, softening or phase transformation effects due to reheating were not considered. Even with this knowledge it is difficult to determine the reason for the differences. The hardening that occurred was due to the formation of untempered martensite. Therefore, the increase in strength would tend to increase the residual stress level. However, the phase transformation to martensite resulted in a volumetric expansion that partially diminishes the thermal contraction. This would tend to reduce the residual stress levels.

An unexpected factor was the occurrence of cracking in the fusion zone. Cracks ranging from 0.1 mm to 2 mm formed beneath the weld surface in the fusion zone. Obviously, the presence of cracks reduced the residual stress levels around the cracks. The presence of a crack was simulated in the model. The simulated crack was placed parallel to the axial direction, about 1 mm from the axial axis of the disk. It was 2 mm long, with the crack tip about 1.5 mm from the weld surface. As expected, the residual stress levels around the crack were significantly reduced (Figure 3). Surprisingly, the reduction was very localized. The effects of the introduced crack began to diminish at only 2.5 mm from the weld centerline, indicating that the presence of a crack in the fusion zone may not significantly change the residual stress levels in the base metal and far HAZ. This was consistent with the comparisons between the measurements and the modeling.

It was concluded in this study that there were some differences between the thermo-mechanically uncoupled and semi-coupled FE, but in general were in good agreement. Both predictions were in very good agreement far away from the fusion zone. Both predictions over-predicted the residual stresses in the fusion zone, probably due to the presence of cracking in the measured sample phase transformations and property changes not accounted for in the model. Preliminary FE analysis indicates that the effects of cracks on the relaxation of residual stresses are localized to the region around the cracks. Therefore, the residual stress predictions in the base metal and far HAZ were not greatly affected by the presence of the cracks.

Evolution of Residual Stresses in a Multi-pass HSLA-100 Weld

The purpose of this work was to describe the evolution of weld residual stresses as a function of each weld layer in a multi-pass, 19-mm thick, HSLA-100 steel plate. This was done to gain knowledge and information of how residual stresses evolve from weld pass to weld pass. Detailed information was maintained which allows models to accurately duplicate the conditions of the welding process. This work is described in detail in references [4] and [5]. This analysis was performed by NSWC and NIST. Neutron diffraction measurements and measurement development techniques were performed by NIST.

A weldment of HSLA-100 steel was prepared using the GMAW process using weld wire produced from a similar plate and using 98% Ar - 2% O shielding gas. Residual stress measurements were made using the neutron diffraction technique. Measurements were made subsequent to each weld layer in order to describe the evolution of residual stresses from layer to layer. Subsequent to completion of the weldment and measurements, 2mm cubes were removed from each measurement location in order to determine the stress-free lattice parameter, d_0 . These values were then utilized to determine the stress values at each stress measurement location. The hydrostatic residual stress results are presented in Figures 4.

It was concluded that large stress gradients existed in both the weld metal and the baseplate. The initial deposition of a weld bead developed neutral stresses to compressive stresses. Subsequent deposition of weld beads resulted in the development of higher tension, to the point that high stress values near the biaxial yield strength were achieved, followed by relaxation with the deposition of additional weld beads. The baseplate developed high tensile stresses adjacent to the weld upon initial deposition of a weld bead, and continued to grow in tension with the deposition of subsequent weld beads. The baseplate also experienced some relaxation once very high tensile stresses were achieved. The tensile stresses in the baseplate proceeded to taper into compression at locations further from the weld (~11+ mm).

It was also concluded from this work that the unstressed lattice parameter, d_0 , varies throughout the fabrication of the weld joint. It is therefore necessary to accommodate changing d_0 values in the weld metal when calculating residual stress values from diffraction data, otherwise large errors can result in the calculated stress value. It was determined that d_0 varied throughout the weld metal locations due to dilution and tempering. The d_0 values were largest in the top weld passes, and tapered toward the baseplate values in the lower passes. The d_0 value varied on the order of 0.001 Å. This variation was sufficient to cause an increase in the calculated residual stress value of 263 MPa.

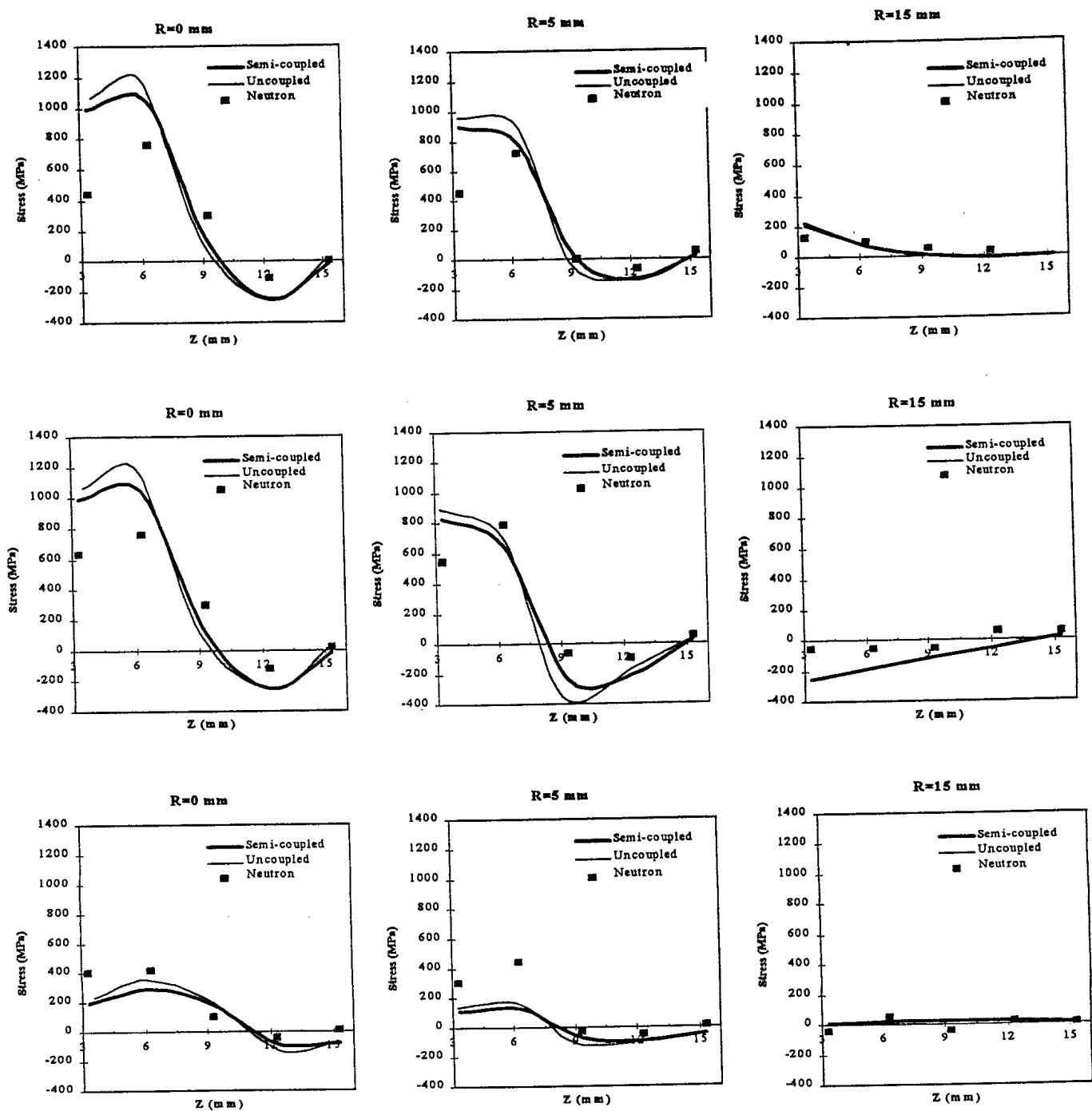


Figure 2. Comparison of neutron diffraction measurements and FEM predictions. Top: Radial Stress, Middle: Hoop Stress, and Bottom: Axial stress, Z = Distance in the normal direction, R = Distance in the radial direction.

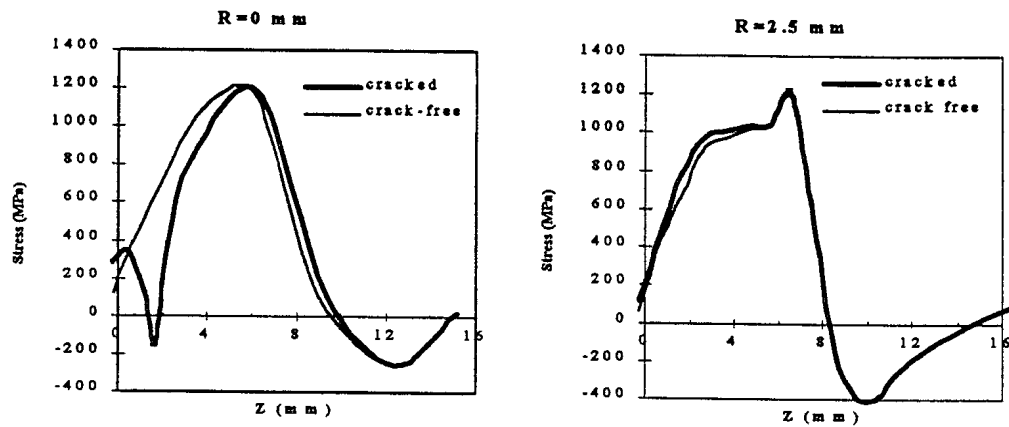


Figure 3. Effect of a single crack on the hoop residual stress distributions using the uncoupled model formulation at radial distances of 0 mm and 2.5 mm from the center of the disk..

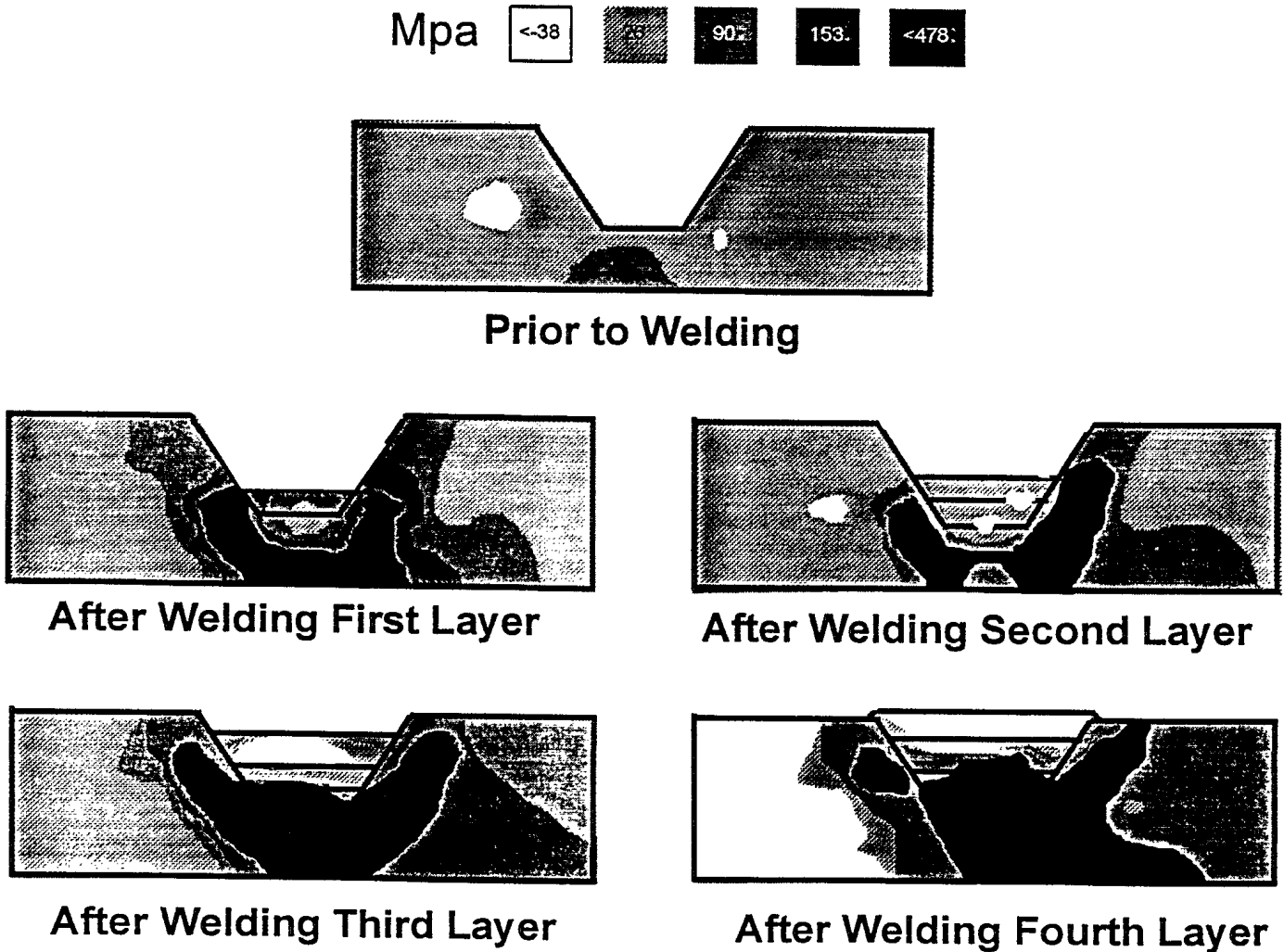


Figure 4. The evolution of the hydrostatic residual stresses.

Modeling of the Evolution of Residual Stresses in a Multi-pass HSLA-100 Weld

A weld solidification model has been developed by NCEMT in Johnstown, PA to aid in the optimization of high strength steels used in ship construction. This model contains the ability to predict residual stress distributions in addition to material properties. This model utilizes the ABAQUS finite-element code. The weld solidification is modeled using an uncoupled 2-D thermo-mechanical analysis with no account for fluid flow or magnetic effects. Individual bead-on-plate welds or multi-pass welds can be modeled using the element re-birth technique. Most of the modeling efforts have focused on GMA welding of high strength steel. To date, good agreement between model results and experimental data has been achieved with experimental data (residual stresses, microstructures, properties, and hardness). Results to date are reported in references [6] through [11].

The model described above has been used to simulate the evolution of residual stresses in a multipass HSLA-100 weld as described in the previous section. A comparison of the results is shown in Figure 5. The results were very similar in many respects. In both cases, large stress gradients existed in both the weld metal and the baseplate. The initial deposition of a weld bead developed neutral stresses to compressive stresses. Subsequent deposition of weld beads resulted in the development of higher tension in previous beads, followed by relaxation with the deposition of additional weld beads. The baseplate developed high tensile stresses adjacent to the weld upon initial deposition of a weld bead, and continued to grow in tension with the deposition of subsequent weld beads. The baseplate also experienced some relaxation once very high tensile stresses were achieved. The tensile stresses in the baseplate proceeded to taper into compression at locations further from the weld.

Some differences did exist. Primarily, the model predicted higher tensile results in the weld metal region and somewhat lower results at regions farther away in the baseplate. At this time, the specific reasons are not clear. However, one postulation is that the clamping forces employed to hold the plate in place were different in the experiment and the model. Since the clamping force was not measured in the experimental analysis, an arbitrary clamping pressure was provided in the model experiment. Although the clamping pressures were unable to be matched, a comparison of the angular distortion of each provides some insight, as shown in Figure 6. The amount of deflection in the actual weldment exceeded the deflection of the model prediction by a factor of 2. The fact that the amount of angular distortion was less in the model experiment, indicates that the clamping pressure may have been higher than the actual. Therefore, it is feasible that due to the increased amount of restraint in the model, higher residual stresses may have developed in the weld zone. The higher residual stresses in the weld zone may have led to more compressive stresses outside the weld zone in order to achieve a balance of forces. This issue will be addressed in future experimentation.

Effects of Grinding on the Surface Residual Stresses in HSLA-100 Steel Bead-on-Plate Weldments.

The initial intent of this project was to determine the effects of GMA welding variables such as preheat, current, voltage, heat input, and etc. on the resulting residual stresses as determined by x-ray diffraction techniques (at Virginia Polytechnic Institute (VPI)). However, it was determined that preparing the baseplate for welding by abrasive grinding had a significant effect on the resulting residual stresses. Initial results indicated that very low tensile stresses existed near the fusion zone and they increased in magnitude at increasing distances away from the fusion zone. Examples of this are shown in Figures 7. In this case, the bead-on-plate welds were deposited using two different preheating temperatures of 24°C and 204°C. In this and other cases it was noted that a maximum value of residual stress, near the yield strength of the material (~700 MPa) or greater, was frequently achieved within a few millimeters of the fusion zone. These residual stress patterns were unexpected and were not consistent with the traditional trends previously observed (i.e. high tensile residual stresses near the fusion boundary and tapering into compression at increasing distance). It was suspected that the grinding stresses, created during pre-weld base plate preparation, were affecting the results. Additional experimentation was performed to verify this.

The intent of additional tests was to eliminate pre-weld grinding stresses while also removing the plate production oxide scale. Additional plates were prepared by first machine grinding the plates to clean metal, followed by vacuum annealing at 650°C for up to 2 hours. Determination of the residual stresses using x-ray diffraction across the surface of the plate indicated that residual stresses due to grinding had been eliminated as a result of vacuum annealing. The average value of residual stresses indicated that the average stress value was $-95 \text{ MPa} \pm 31 \text{ MPa}$. These values were consistent with values obtained using as-received plate material. The average stress value was achieved using an anneal time of 1 and 2 hours. The standard deviation was improved somewhat by annealing for 2 hours. It was concluded, at this point, that vacuum annealing reduced grinding stresses and prohibited the formation of scale.

After vacuum annealing, GMAW bead-on-plate welds were placed on the surface using preheating temperatures of 24°C and 204°C. Subsequent to welding, the surface residual stresses were determined using x-ray diffraction techniques at VPI. The results are plotted in Figures 8 and 9.

If the simplest case is assumed, that grinding stresses and welding stresses are linearly additive, then subtracting the stress-relieved data (welding stresses only) from the non-stress-relieved data (welding + grinding stresses) results in the residual stresses due to welding only. It is immediately apparent that grinding significantly changed the magnitude and even the sign of the surface residual stresses. The grinding stresses increased as the distance from the fusion zone increased. This is because the heat of welding provided a greater stress relief treatment in the higher temperature regions of the HAZ. Due to this heating effect, it was also seen in most cases that the data representing "welding stress only" and "welding + grinding" approach similar values at positions close to the fusion line. This indicates that the grinding residual stresses were reduced in this region. Using this technique it can be seen that the surface residual stresses due to welding were reduced as the preheat temperature increased from 24°C to 204°C.

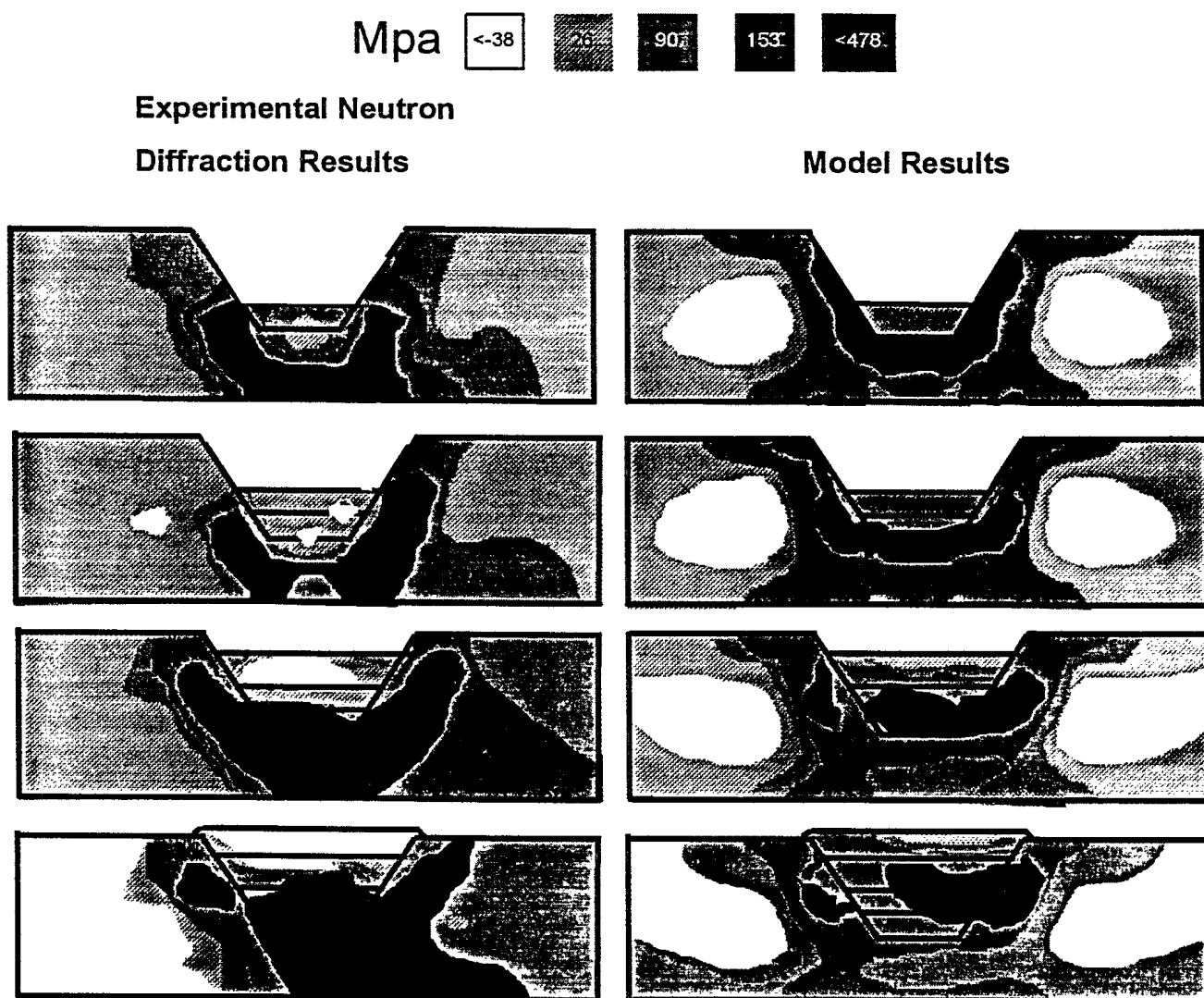


Figure 5. Comparison of the hydrostatic residual stresses as determined by neutron diffraction and predicted by a model.

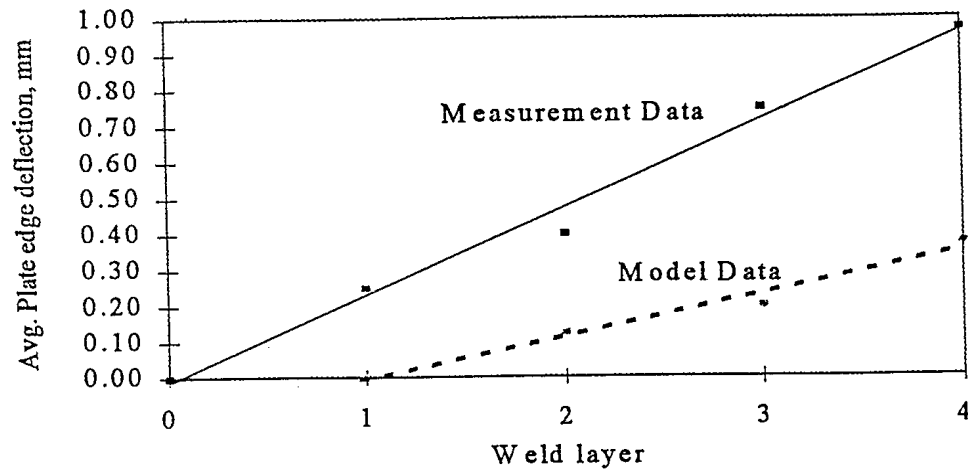


Figure 6. Comparison of the distortion that occurred in the actual welded plate and the model plate.

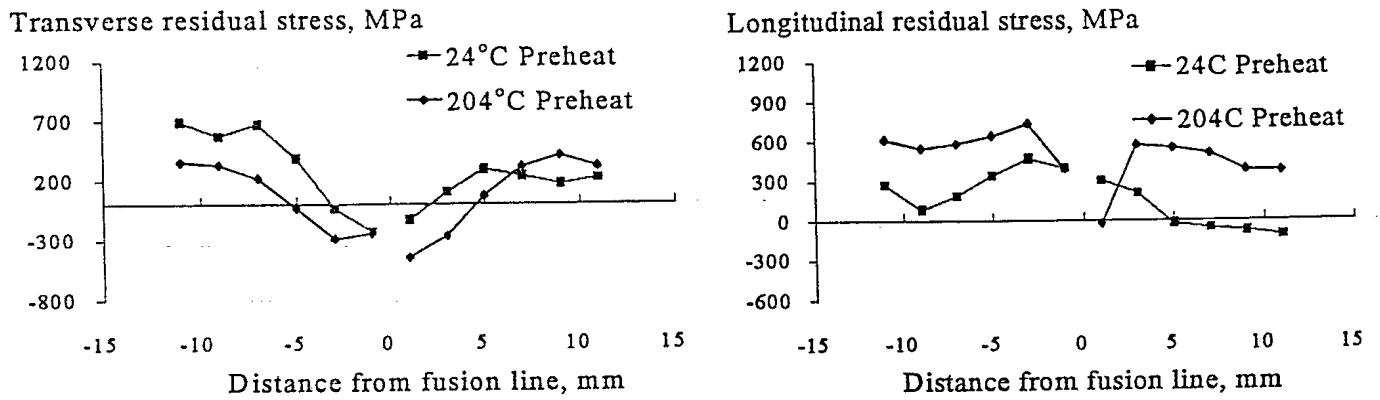


Figure 7. Transverse and longitudinal residual stress as a result of pre-weld grinding and welding.

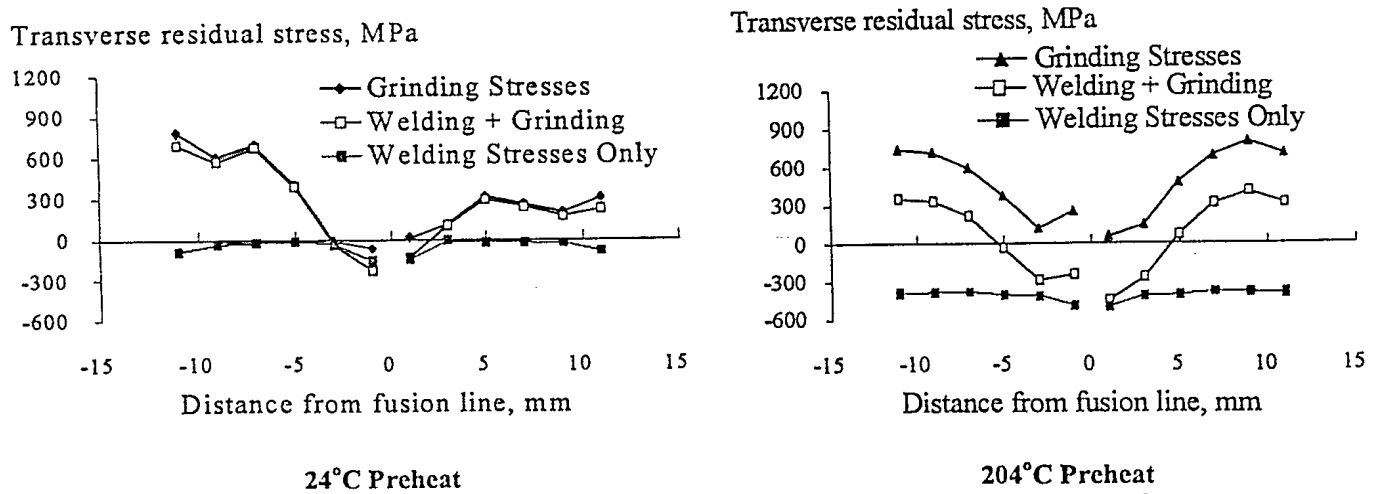
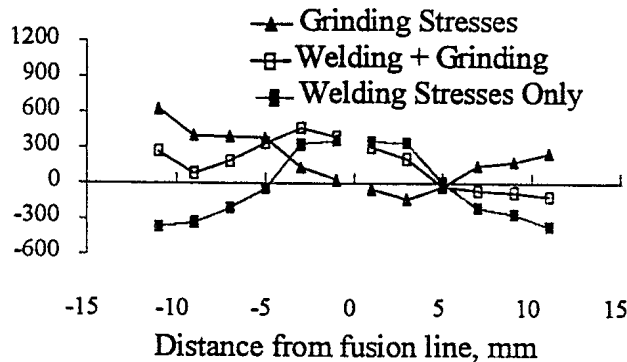


Figure 8. Separation of transverse residual grinding and welding stresses for 24°C and 204°C preheat.

Longitudinal residual stress, MPa



Longitudinal residual stress, MPa

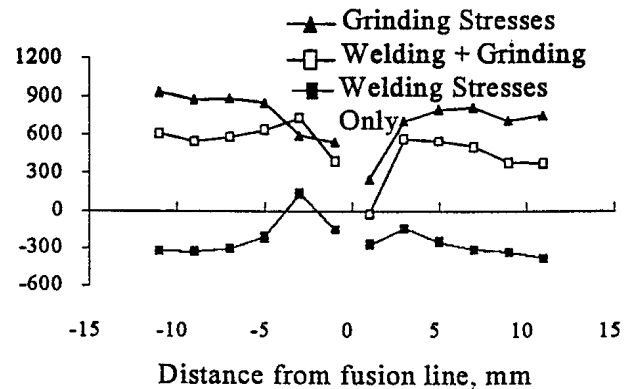


Figure 9. Separation of longitudinal residual grinding and welding stresses for 24°C and 204°C preheats.

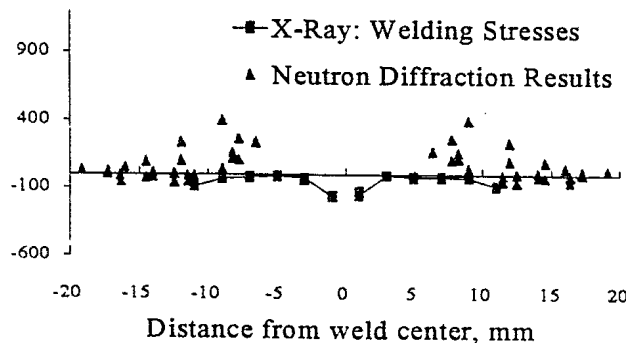
In terms of model verification, it is important to isolate the residual stresses due to welding in order to accurately compare results from experimental x-ray analysis techniques to the model predictions. This approach is acceptable for the scientific study of residual stresses, but in actual shipbuilding or welding applications where pre-grinding is standard procedure, the final surface residual stress state will be very unlike what would be expected due to welding only.

It has also been shown that x-ray diffraction is a surface analysis technique and does not necessarily represent the bulk stress state. This is illustrated in Figure 10. A comparison of x-ray diffraction data and neutron diffraction data is made in Figure 10. The neutron diffraction data was extracted from the section above entitled "Evolution of Residual Stresses in a Multi-pass HSLA-100 Weld". This data represents the first weld pass placed in the multi-pass weld. The distances, regardless of the position within the thickness of the plate, were calculated to the center of the weld bead. It can be seen that the bulk stress state, represented by the neutron diffraction data, does not compare well with the surface stresses determined by x-ray diffraction.

It was concluded in this study that in order to isolate the development of surface residual stresses due to welding only, it is necessary to prepare the baseplate for welding with a means that will not itself induce residual stresses. However, surface stresses may be analyzed in the fusion boundary and the near HAZ even when pre-existing grinding stresses were present. Further details of this study can be found in references [12] and [13].

Ongoing work in this area includes the measurement of residual stresses associated with weld cracking tests such as the Welding Institute of Canada (WIC) weldability test using x-ray diffraction. This data will be used to characterize the residual stresses associated with various weldability tests.

Transverse residual stress, MPa



Longitudinal residual stress, MPa

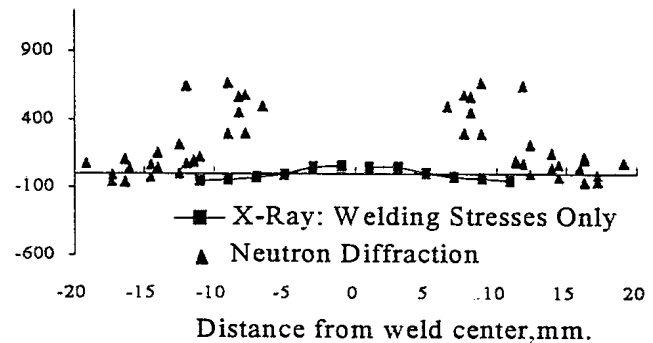


Figure 10. Comparison of neutron diffraction and x-ray diffraction results for the transverse and longitudinal residual stress component.

Prediction and Prevention of Distortion in Thin Section Panels

This work was performed by the Edison Welding Institute and its partners in the Navy Joining Center (NJC). This was one of several tasks funded by NJC and managed by the Navy Mantech Program. This program was introduced to aid in the mitigation of distortion problems in *Arleigh Burke* Class destroyers (DDG-51). Support has also been provided by the DDG-51 program office and by the Naval Surface Warfare Center (NSWC).

Welding induced distortion both degrade the performance and increase the cost of the fabricated structure. While flame straightening is an effective method of reducing welding induced distortions to within fairness requirements, it is both cost and labor intensive. A better alternative would be to limit pro-actively and control distortion induced by welding as part of the fabrication process. Progress towards this goal is supported by a methodology that can predict the anticipated level of distortion in a fabricated structure from inputs of basic welding and design variables, such as that developed by Michaleris and DeBiccari [14]. The objective of this work was to determine likely candidates that may be employed to mitigate distortion in the fabrication of stiffened, thin-section panels. In doing so, the primary distortion modes were identified, a predictive methodology was developed, thermo-mechanical properties were developed in support of the predictive methodology, and potential solutions were evaluated using the predictive methodology. Details of this work are presented in reference [1].

In order to identify the distortion modes, multi-stiffener laboratory mock-ups having many features similar to production fabrication and design was adopted (e.g. material thickness and grade, stiffener size and spacing). The mock-up is illustrated in Figure 11. The plate was 4.76 mm thick AH-36 steel cut to a final dimension of 1.2 m x 1.2 m. The longitudinal stiffeners (102 mm x 102 mm x 2.3 kg) were placed at a spacing of 68.6 cm on center. The transverse stiffeners (102 mm x 254 mm x 5.5 kg) were also placed at a spacing of 68.6 cm on center. Although transverse stiffeners are placed much further apart in actual production, this spacing permitted multiple stiffeners for this configuration. The typical fillet weld leg sizes for longitudinals were 3.2 mm to 4.8 mm, and for the transverse stiffeners, 4.8 mm. The FCAW process was used with a 1.32 mm dia. E71T-1 electrode and 100% CO₂ shielding gas. Out-of-plane distortion measurements were made using a dial indicator inserted into an array of vertical tubes situated beneath the plate of interest. Transient out-of-plane distortion measurements were also made using mechanical linear voltage displacement transducers (LVDT's). The motion of the plate surface during welding was determined by mounting the LVDT's under the mock-up and monitoring the change in their output with time.

The results of the distortion measurements due to welding the first and second longitudinal stiffeners are shown in Figure 12 for a 709 J/mm, 4.8 mm fillet weld mock-up. This sequence of figures illustrates how the out-of-plane distortion accumulated as a result of welding the longitudinal stiffeners. Welding of the longitudinal stiffeners produced buckling as evidenced by a characteristic S-shape. Buckling was also verified by the panel's stability in multiple configurations, which is a characteristic of buckling distortion only. By proper placement of force, the out-of-plane displacement was reversible. The panel popped suddenly as the mode shape switched sign. Welding of the transverse stiffeners removed much of the distortion due to the small transverse spacing. The spacing in actual production is typically much larger. Differential plots revealed the contribution of welding each stiffener to the total distortion. The longitudinals produced primarily buckling, while welding the transverse stiffeners produced angular distortion. It was therefore concluded that the dominant mode of distortion was buckling.

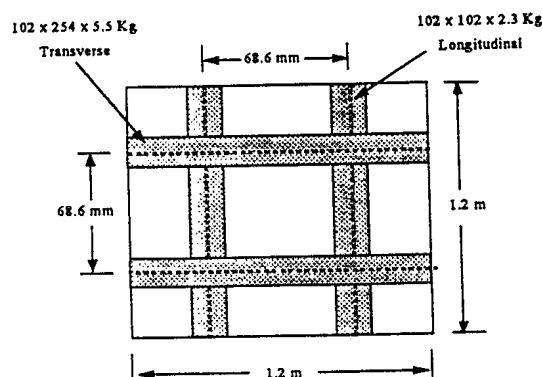


Figure 11. Laboratory stiffened panel mock-up.

Transient out-of-plane distortion measurements also showed the development of buckling distortion. Figure 13 shows typical traces from three transducers placed along one edge of the mock-up. The sudden change in these traces indicates buckling.

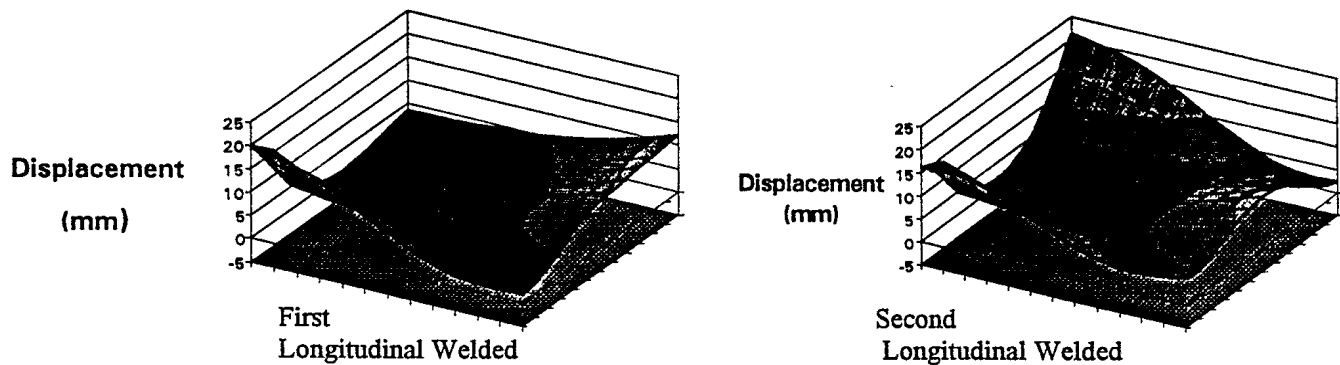


Figure 12. Distortion after welding the first and second longitudinal (709 J/mm, 4.8 mm weld).

The compressive forces necessary to cause buckling are generated by the shrinkage which results upon the solidification of the weld metal. During cooling of the weld metal, the longitudinal shrinkage upon solidification of the weld metal is resisted by the cooler baseplate. In effect, the shrinkage of the weld metal applies a compressive force on the surrounding base plate in the longitudinal direction. When sufficient force is developed, buckling occurs.

The methodology developed by Michaleris and DeBiccari [14] for determining the occurrence of buckling in thin section panels was employed in this analysis. The predictive methodology consisted of two models. A two-dimensional model was used for weld process simulation. This model depended upon both welding parameters and on characteristics of the design local to the weld joint. The output of this model was the driving force for buckling, or *The Equivalent Applied Thermal Buckling Strain, $\epsilon_{\tau-applied}$* . A three-dimensional elastic-plastic structural model was utilized to evaluate the stiffness of the structure, or the *Equivalent Resistance to Thermal Buckling, $\epsilon_{\tau-resistance}$* . Assessment of buckling for a particular combination of design and welding variables was a simple comparison of the resistance to buckling and the driving force for buckling. In theory, if the driving force is greater than the resistance, the structure is expected to buckle. The ratio of the applied strain to the resistance strain was termed "Buckling Ratio". Hence the following equation.

$$\text{Buckling Ratio} = \epsilon_{\tau-applied} / \epsilon_{\tau-resistance}$$

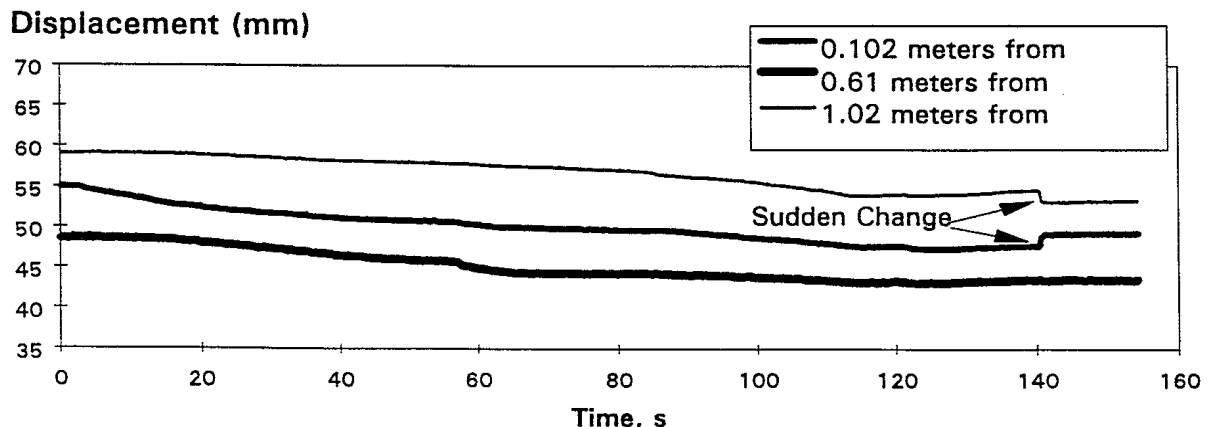


Figure 13. Transient out-of-plane distortion measurements recorded on a laboratory mock-up.

Upon comparing the buckling ratios, generated by the methodology, to the occurrence of buckling in a series of mock-ups, it was determined that the critical ratio required for buckling was a value of 0.75. In order to achieve this value

in 4.8 mm plate it was necessary to reduce the welding heat input to 315 J/mm in order to avoid buckling distortion. An increase in the heat input to 354 J/mm was sufficient to cause buckling as demonstrated in Figure 14.

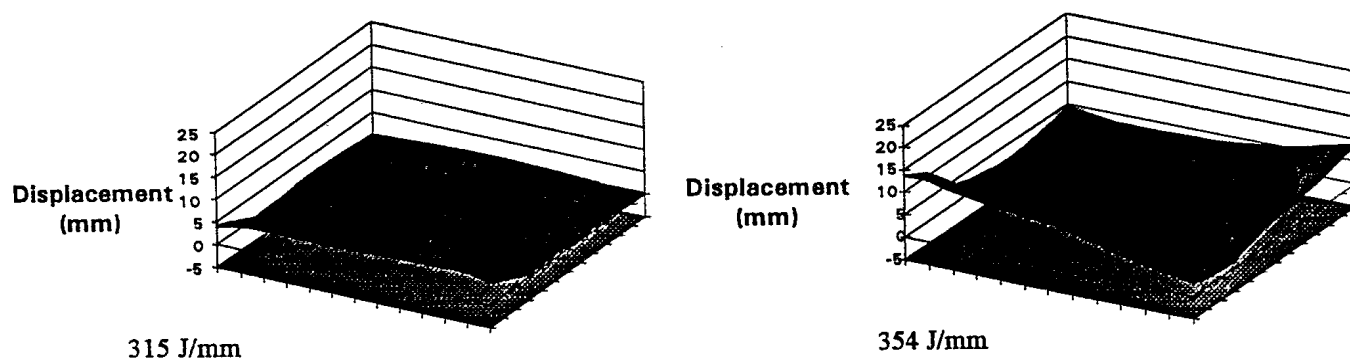


Figure 14. Measured out-of-plane distortion after the first longitudinal stiffener was welded for 315 and 354 J/mm welds.

This methodology was then applied to a 4.76 mm -thick, 6.1 m - long by 2.6 m - wide stiffened, shipyard production panel. This panel contained 3 longitudinal and 3 transverse stiffeners. The results are shown in Figure 15. It can be seen in this case that a heat input of about 200 J/mm is required due to the reduced stiffness of the larger geometry. This heat input will not produce the design minimum fillet weld size using the flux core arc welding process. A shipyard mock-up of this configuration was also prepared and welded at a heat input of 354 J/mm. The result was that buckling still occurred. It was concluded in this study that buckling distortion cannot be eliminated from the current design by better control of the welding practice even if the fit-up between the shell plating and the longitudinal stiffeners can be improved to a zero-gap condition.

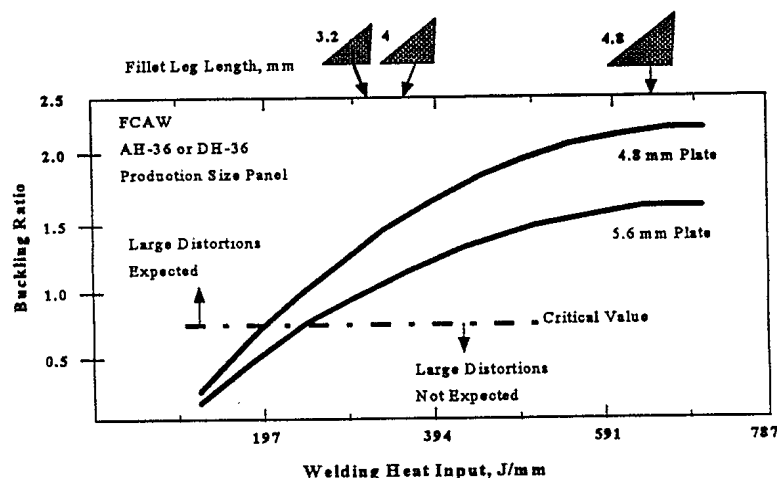


Figure 15. Results of buckling predictions for shipyard size panels.

Although heat input control or fit-up cannot eliminate buckling distortion, some other alternatives are currently being investigated. They are 1) the use of intermittent fillet welds, 2) the use of flatter initial base plate, and 3) thermal tensioning. Although the use of intermittent fillet welds is not permitted with the current design due to fatigue, corrosion, and shock resistance concerns, the initial results are promising, as illustrated in Figure 16. Two panels were fabricated using continuous fillet welds at low heat input and one at a relatively high heat input. It can be seen in Figure 16 that welding with intermittent fillet welds can dramatically reduce the buckling distortion even when the intermittent welds are much higher heat input.

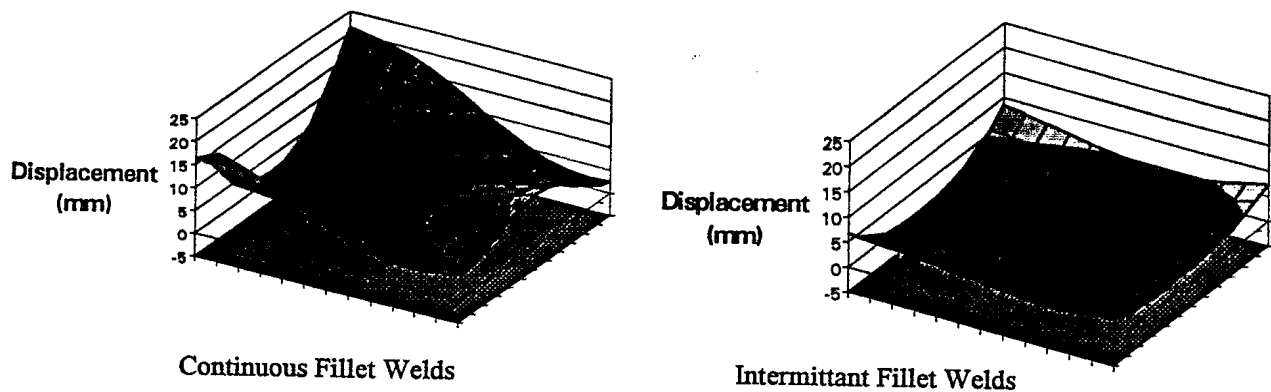


Figure 16. Out of plane distortion measurements after welding two longitudinal stiffeners for continuous (709 J/mm) and intermittent fillet welds (1574 J/mm).

The idea of using flatter initial plate to control the final overall distortion has been debated for several years. However, Figure 17 indicates that some benefit may be realized. Using the methodology described above, the effect of initial plate fairness on final distortion was investigated. The initial unfairness was varied from 0.05 mm to 4.8 mm at the mid-span of the plate. The curves indicate that for each initial unfairness state, the displacement increases at a fairly low rate with applied load, and at a given load the rate increases dramatically. The greater degree of initial unfairness, the lower the required load at which the relationship between load and displacement accelerates. Not only do these curves indicate that flatter initial plate is beneficial, but that current distortion mitigation techniques may be more effective if flatter initial plate is utilized.

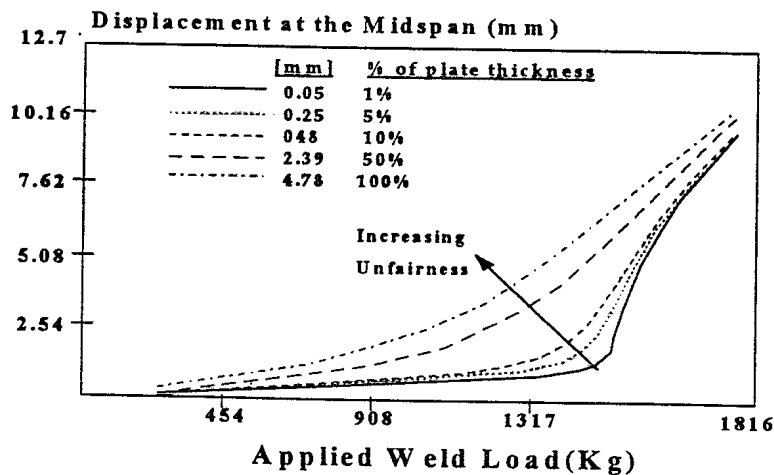


Figure 17. The effect of initial plate unfairness on resulting buckling distortion.

Thermal tensioning is a technique by which the compressive forces developed during welding are anticipated and counteracted by applying a tensile load to the weld joint prior to and during welding by imposing a preset temperature gradient through the use of heating and cooling elements. Cooling is applied beneath the plate along the length of the weld joint while heating is applied on both sides of the weld joint. In order to be effective, the proper thermal gradient must be determined. The predictive methodology, discussed above, was utilized to determine thermal tensioning conditions which will result in elimination of buckling. These conditions were duplicated on actual panels to test the validity of the model. Figure 18. displays the results. It can be seen that for a weld heat input of 709 J/mm, which previously caused buckling, that buckling distortion was eliminated with only angular distortion remaining. It was also shown that the maximum residual stresses were reduced from 349 MPa to 140 MPa. Angular distortion can be eliminated by applying an elastic pre-bending before and during welding.

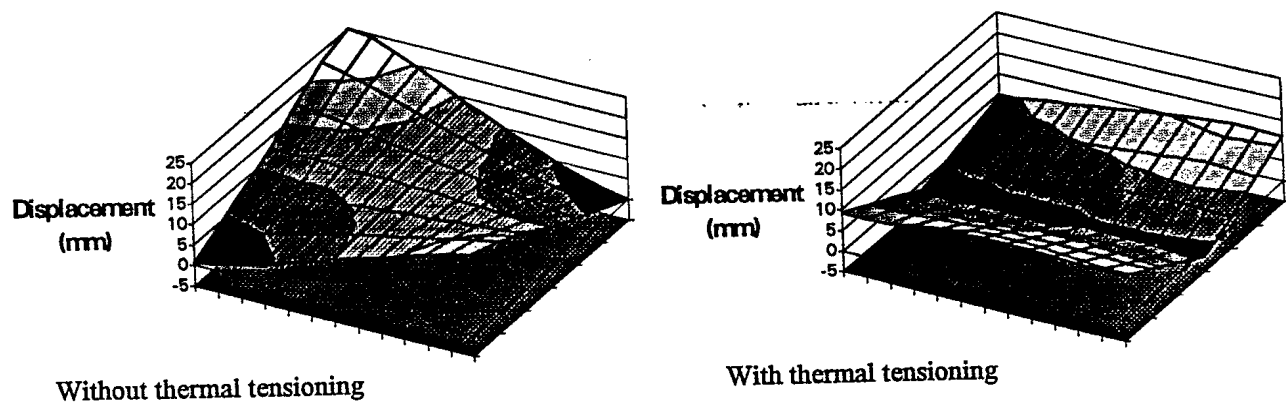


Figure 18. Comparison of out of plane distortion with and without thermal tensioning as a result of welding one longitudinal stiffener at 630 J/mm.

The sensitivity of this predictive methodology was evaluated by analyzing the effect of variations in the material yield strength. The variation of yield strength with temperature used for the weld process simulations employed a room temperature yield strength of 356 MPa, the specified minimum for the material. However, the actual plates used in this investigation have measured room temperature properties ranging up to 524 MPa. The study of the effect of these differences was motivated by the fact that most procured materials exceed the specified minimum tensile requirement. In this study, the variation of strength was allowed to increase by 30%. Since the formation of residual stresses and distortion are highly dependent upon high temperature tensile properties, high temperature tensile data was developed at NSWC as shown in Figure 19. It was also anticipated that some variations in these properties exist as well. Therefore, increases in the temperature range of 600°C to 700°C of up to 30% were also analyzed. It was demonstrated that changes in the applied strain as a result of these variations ranged from -0.2% to 4% difference from the baseline values. It was concluded that these variations need not be accounted for in the assessment for the propensity for buckling.

Upon reviewing the closed form solutions to the structural Eigenvalue analysis, it was concluded that the critical buckling load should scale with the square of the plate thickness. Upon comparing the analysis outputs with the scaled values for plate thickness, it was determined that the scaled values were within 5.8% of the analysis output. Thus, values of the structural resistance strain calculated for one thickness were found to be scaleable to predict results for other thicknesses over a limited range.

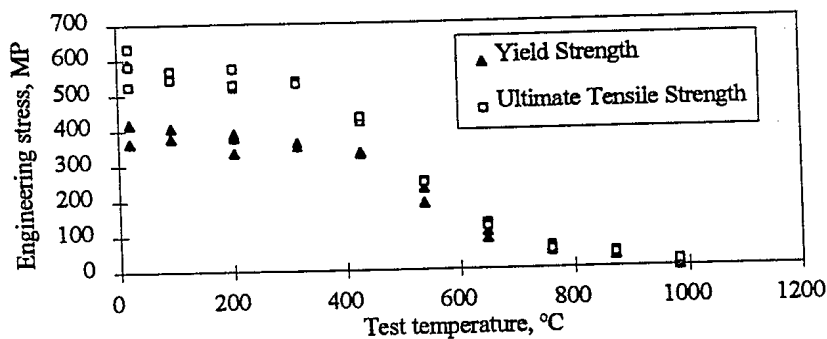


Figure 19. High temperature property data for AH-36 steel.

Development of Thermo-Physical and Thermo-Mechanical Property Data

The availability of thermo-physical and thermo-mechanical property data is essential for appropriate model performance. This data is not readily available or does not exist. This data is either developed on a case by case basis, or is extrapolated from information on similar materials. Even when best engineering judgment is used, extrapolation can lead

to gross errors in the model due to the sensitivity of the output to the accuracy of the input parameters, and the cumulative effects of small errors. The direct use of experimental data for the materials of interest is often the most desirable when it is available.

Currently, there are three programs being performed at the National Center for Excellence in Metalworking Technology (NCEMT) in Johnstown, Pa. which include the development and collection of thermo-mechanical and thermo-physical property data. They are entitled "*Thermo-physical Properties in Metalworking Processes*", "*Thermo-mechanical Processing Initiative*", and "*Atlas of Formability*". The following sections describe each of these programs. Although these programs are not specifically related to welding, it is recognized that the data is also applicable to any high temperature metalworking process, including welding.

Thermo-Physical Properties in Metalworking Processes

The objective of this project is to provide reliable thermo-physical property data that can be used in the optimization of metalworking processes involved in the production of DoD weapons systems. The primary benefit will be realized by the DoD and their vendors attempting to model, simulate, control, and optimize metalworking processes. The data, when integrated in process simulation, will be an essential tool to the manufacturing engineer for the prediction and optimization of various metalworking processes. The data will exist as a computerized database that will be available to the DoD and their vendors. Currently, the electronic database is under development, surveys are being performed to determine the needs of the metalworking community, and efforts to evaluate process simulation sensitivity, sensitivities to thermo-physical properties, estimation of property data, and evaluation of needed phase diagrams have begun.

Thermo-Mechanical Processing Initiative

The objective of this project is to develop and demonstrate technologies that can be used to optimize thermo-mechanical processes. The project is focused on improving the technologies needed to enhance the production of components. These technologies include improved process and material simulation techniques to predict and control microstructure and defects during processing as well as the advanced measurement techniques needed to verify the results. Other technologies include development of the advanced experimental techniques to provide the detailed material property data required for accurate simulation. Although the thermo-mechanical property data is being developed for specific manufacturing processing of components, the data is also applicable to weld modeling.

Atlas of Formability

The objective of this project is to generate forming data needed to develop and optimize forming processes for weapon system components. These data include flow behavior under industrial processing conditions (a wide range of temperatures and strain rates) and resulting microstructural changes for more than 150 materials. The material flow data is critical for the successful application of advanced analytical tools or techniques such as finite element modeling. Mechanical properties under investigation include: stress-strain relations at elevated temperatures and various strain rates, workability, forming limits, and strain to fracture. Once again, this data will be useful in weld modeling also.

The Effect of Residual Stresses on Fatigue Performance.

The role of residual stresses on fatigue crack growth behavior is currently being studied at Northwestern University and the University of Missouri. The combined effort is investigating the role of micro- and macro- residual stresses on the initiation and propagation of fatigue cracks in multiphase metallic materials using x-ray microbeam diffraction and neutron diffraction techniques. Presently, the effects of pre-existing stresses on fatigue analysis results and crack propagation behavior has been analyzed using x-ray diffraction techniques. The x-ray beam used for stress measurements was 220 μm in diameter formed with a linearly tapered capillary. The capillary focuses the x-rays, provides good spatial resolution to capture stress gradients, and provides adequate intensities for diffraction experiments. The material under investigation is 1080 steel containing 14% spherical Fe_3C particles in a ferrite matrix. The intensity from the capillary allows for the measurement of stresses in both phases, wherein they can be separated into macro- and micro-stresses. For the following results however, data for the macro-stress is presented, which by definition are equal between phases, and therefore only the ferrite stress data is shown.

Triaxial measurements were made near the crack tip of a compact tension specimen using the Fe 211 reflection and tilting to 31 different $\psi\phi$ angles and solving the stress tensor by least squares. This removed the assumption of a negligible σ_{33} component (normal to the surface) over the $\sim 30\text{ }\mu\text{m}$ x-ray penetration depth.

Figure 20 shows the triaxial stress components at the tip of a fatigue crack under increasing applied load. The crack (15.2 mm long) was grown by machining the 1080 steel into a compact tension specimen, which was notched with a jeweler's saw and fatiguing at 3 Hz, $R=-0.1$ and $P=940\text{ kg}$. After growing the crack to 15.2 mm the sample was statically loaded by pushing against the crack faces with a set screw. The stresses were then measured at the crack tip with a $220\text{ }\mu\text{m}$ x-ray beam. Figure 20 provides information on (a) the triaxial nature of the stresses experienced by the crack tip during loading, and (b) the interaction of residual and loading stresses. At zero load (the residual state) all three components are compressive, a result of the extensive plasticity associated with the crack tip singularity. The σ_{33} component, though smallest in magnitude, is finite at the tip even under the "plane stress" conditions at the surface. As the load is increased, the stresses increase rather linearly, which suggests that the applied stresses superimpose on the residual stresses at the tip. The stresses remain compressive until about $13.5\text{ MPa}\cdot\text{m}^{1/2}$ thus the crack tip experienced compression over $\sim 30\%$ of its loading cycle. Since the crack will only propagate under tensile load, this is clear evidence of crack-tip shielding due to residual stresses generated by the crack itself. The implication is that the initial compressive stress state must be taken into account to accurately characterize the material performance. Otherwise, an overestimation of the fatigue performance will result. It is also clear that the existence of residual stresses is directly additive to the applied loads.

Figure 21 illustrates how the stress field of a growing fatigue crack interacts with a pre-existing residual macro-stress field. The stresses were introduced into a 1080 steel specimen by plastically force-fitting a plug into an undersized hole ($\sim 2\%$), which resulted in the tangential profile shown prior to crack growth. The crack was grown as described above, and the stresses were again measured using the x-ray diffraction technique described above. The stresses were predominantly tensile, which should accelerate crack growth. However, there was little difference in growth rates between these and the control samples. The explanation for this lies in the stress field pattern that exists during crack growth. The crack tip stress field appeared to obliterate the existing residual stresses out to about 1mm ahead of the tip so that the growing crack is never subjected to these stresses. Ahead of the tip-affected region the residual stresses are similar to the pre-crack values, which suggests that fatigue did not result in appreciable stress fading. In fact, the stresses are actually higher after fatigue. Thus it was the generated crack-tip stress field, rather than the fading of existing residual stresses, that led to the insensitivity of growth to pre-existing stresses. Future work is planned to evaluate the resulting stress fields in the presence of residual stresses of higher magnitude. Other work related to this topic can be found in reference [15].

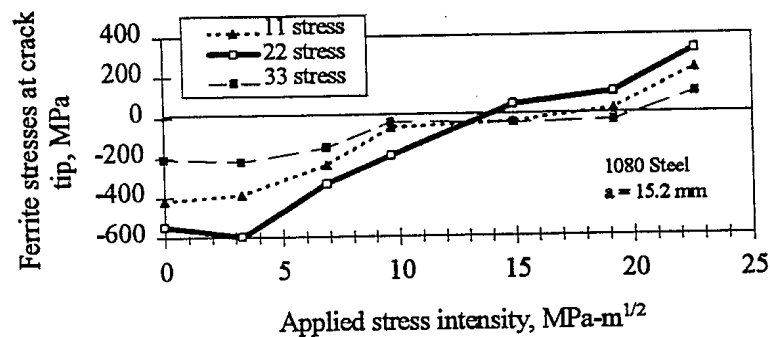


Figure 20. Triaxial ferrite stresses at fatigue crack tip under applied tensile load.

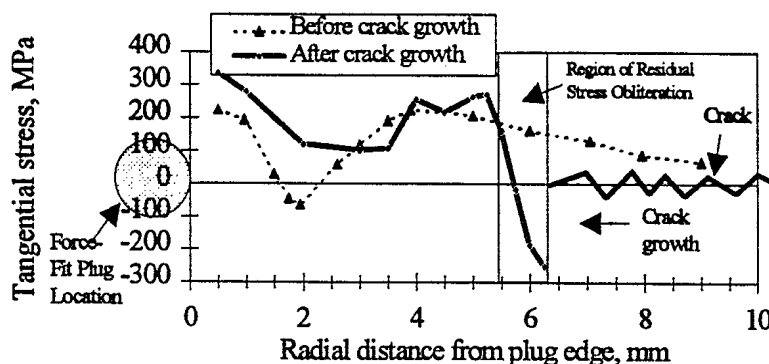


Figure 21. Tangential stresses in residual macrostress sample before and after crack growth.

The Effect of Weld Residual Stresses on Stress Corrosion Cracking (SCC)

The effect of weld residual stresses on stress corrosion cracking initiation and growth in HY-130 steel was investigated by NSWC using the trough weld test. The objective was to determine if weld residual stresses alone are sufficient to initiate or propagate SCC. Eighty four trough welds were prepared in 51 mm plate and subjected to seawater and impressed currents at -1.0 and -0.8 volts for up to three years. The trough weld test is a highly restrained, simulated repair weld which is shaped like a trough and is approximately 22 cm long by 38 mm deep by 63.5 mm wide. Seventy of the welds were produced using GMAW only. The remaining welds were prepared using GMAW and SMAW. The majority of the trough was filled using GMAW with the final 2 layers being SMAW. After welding, the welds were machined flush with the surface of the plate and inspected for cracks using magnetic particle inspection (MT) and ultrasonic inspection (UT). It was determined that the GMA weld metal did not contain any measurable cracks and all welds capped with SMAW contained several transverse indications ranging up to about 9.5 mm in surface or near surface length and about 1.6 mm in depth. Upon exposure to the corrosive conditions described above, it was determined that no cracks were initiated in the GMA weld metal. It was also concluded that pre-existing cracks in the SMAW welds did not grow significantly. Subsequent measurement of surface residual stresses using neutron diffraction data indicated that a significant amount of compressive residual stresses existed at the surface. Therefore, initiation or growth of cracks due to SCC would not be expected. However, there was some evidence that crack growth may have occurred, and in two instances cracks appeared to have grown significantly to 9.5 mm in depth. But due to discrepancies in crack location data, and early closure of the program, it was determined that there was insufficient data to verify actual crack growth and to therefore attribute crack growth to the presence of the residual stress field.

Summary

This paper describes some of the current U.S. Navy efforts geared toward managing residual stresses and distortion during weld fabrication. These efforts include model development, model verification, thermo-mechanical and thermo-physical property development, the generation of residual stress measurement data using x-ray and neutron diffraction techniques, the analysis of the effects of residual stresses on fatigue and stress corrosion cracking, and the use of weld residual stresses to achieve desired shapes in part manufacturing.

Due to the complexities involved in weld residual stress development, significant emphasis has been placed on modeling. The importance of experimental data for model development and validation has been emphasized. Although in their initial stages, programs have been initiated which are geared toward developing data bases to house thermo-mechanical and thermo-physical properties specifically for modeling purposes. In the past, data such as this has been developed in order to determine performance directly related to service conditions of materials. Therefore, there is a lack of data for many materials at conditions not typically encountered in service. In time, as these databases grow, modeling will continue to be enhanced.

Some of the capabilities of the current existing models were demonstrated. It was shown that there were some differences between FE models and experimental results, but in general were in good agreement. However, it was also shown that residual stress development is highly dependent upon the details of the fabrication process and the material properties and characteristics. Little difference between thermo-mechanically coupled and uncoupled FE results were demonstrated, but additional work is necessary since the work presented here did not include phase transformation effects or varying material properties representative of remelted or reheated material. Preliminary results indicated that the presence of cracking results in a reduction in the residual stress magnitude, but the effect was localized and therefore had no effect on the residual stresses far away from the crack location. Analysis also indicated that the amount of restraint that exists during welding affects the resulting stress magnitude and distribution, contributing to some differences between model analysis and measurement results.

It was demonstrated that careful experimental techniques for measuring residual stresses must be employed to obtain reliable neutron diffraction and x-ray diffraction results for comparing to model analysis. It was shown that welding creates a wide variation in material properties, and can therefore significantly affect measurement results. The reasons for this were attributed to dilution and thermal cycling that occurs during welding.

It was also shown that when analyzing x-ray diffraction results, it is important to realize that the technique is a surface analysis method and can therefore be influenced by surface condition. Grinding stresses played an overwhelming role in masking the surface residual stresses developed by welding. However, the grinding stresses were able to be subtracted from the overall stress state to determine the surface stresses due to welding only. A comparison of surface residual stresses and bulk, through thickness stresses indicated that the surface stress state is not representative of the internal stress state. It is therefore necessary to carefully plan experimental techniques and procedures that will be appropriate for the validation of model results.

It was shown how the iterative interaction between the development of empirical relationships and modeling can be beneficial in providing valuable information toward understanding and solving problems related to weld residual stresses. The application of an empirical model to the distortion of stiffened thin section panels provided useful information relative to the options available for mitigating distortion. It was shown that simply reducing heat input was not a feasible, but intermittent welding and thermal tensioning could provide the desired reduction in distortion. The data generated by this empirical model also suggested that the initial plate flatness could also provide some benefit regarding distortion mitigation.

Efforts were also described which focused on the effects of residual stresses on fatigue cracking and stress corrosion cracking. In a study on the effect of residual stresses on stress corrosion cracking, it was determined that there was insufficient data to reach a logical conclusion. In the study on the effects of residual stresses on fatigue, it was shown that residual stresses play an important role in determining fatigue properties of materials. It was concluded that if compressive residual stresses are not accounted for in fatigue specimens, that significant errors can result, overestimating the fatigue performance of a material. It was also shown that there was no difference in the fatigue crack growth rate of specimens containing residual stresses and those that did not. This was because the crack tip stress field appeared to obliterate the existing residual stresses out to about 1mm ahead of the tip so that the growing crack is never subjected to these stresses. Ahead of the tip-affected region the residual stresses were similar to the pre-crack values, which suggests that fatigue did not result in appreciable stress fading. In fact, the stresses were actually higher after fatigue. Thus it was the generated crack-tip stress field, rather than the fading of existing residual stresses, that led to the insensitivity of growth to pre-existing stresses.

Acknowledgments

This work was funded by the Office of Naval Research (ONR), in support of the Exploratory Development and Manufacturing Science and Technology Programs. The particular efforts of G. Yoder (ONR), S. Linder (ONR) and B. Cole (Naval Sea Systems Command, PMS400D) are greatly appreciated. Without their vision, the advancements in the area of weld residual stresses and distortion would not be possible.

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